PB83-194704

Estimates of Isoprene and Monoterpene Emission Rates in Plants

Northrop Services, Inc.
Corvallis, OR

Prepared for

Corvallis Environmental Research Lab., OR

Mar 82

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completir

1. REPORT NO.	2.	3. PB83-194704
EPA-600/J-82-196	JOURNAL ARTICLE	

4. TITLE AND SUBTITLE	5. REPORT DATE
Estimates of Isoprene and Monoterpene Emission Rates In Plants	1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Rosemary C. Evans, David T. Tingey, Marcia L. Gumpertz, and Walter F. Burns	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Northrop Services, Inc., and U.S. Environmental Protection Agency 200 SW 35th Street Corvallis, Oregon 97333	11. CONTRACT/GRANT NO. 68-03-2650
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED inhouse
Environmental Research Laboratory U.S. Environmental Protection Agency Corvallis, Oregon 97333	14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES

Published in Botanical Gazette, Vol. 143, No. 3: 304-310, 1982

16. ABSTRACT

A range of plant species, including crops, shrubs, herbs, and trees, was surveyed to determine the magnitude of isoprene emissions. In studies to determine if plants emitted isoprene, greenhouse-grown plants were encapsulated in impermeable plastic bags and kept in a growth chamber for 2 h at 30C and a photosynthetic photon flux density of ca. 350μE $m^{-2}s^{-1}$. To estimate emission rates, greenhouse-grown plants were conditioned in a growth chamber and transferred to a controlled-environment gas-exchange chamber. Gas samples from either the encapsulation bags or gas-exchange chamber were collected, concentrated cryogenically, and analyzed by gas-liquid chromatography. The occurrence of isoprene and monoterpenes was confirmed by combined gas chromatography-mass spectrometry. Of the 54 plant species tested, 37 emitted isoprene. Isoprene emission rates (28C and 1,000μE $m^{-2}s^{-1}$) for 16 species ranged from 0 to 38.5μg carbon $g^{-1}h^{-1}$. Monoterpenes were detected from six species and emission rates ranged from 0.01 to 3.53μg carbon $g^{-1}h^{-1}$. The encapsulation technique permitted rapid identification of species that emitted isoprene. The emission rate data confirmed the preliminary isoprene ranking and demonstrated the differences between monoterpene and isoprene emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	unclassified	8
	20. SECURITY CLASS *(This page)*	22. PRICE
	unclassifed	

EPA Form 2220-1 (9-73)

EPA-600/J-82-196
JOURNAL ARTICLE

BOT. GAZ. 143(3):304–310. 1982.

0006-8071/82/4303-0008$02.00

ESTIMATES OF ISOPRENE AND MONOTERPENE EMISSION RATES IN PLANTS

ROSEMARY C. EVANS,* DAVID T. TINGEY,† MARCIA L. GUMPERTZ,* AND WALTER F. BURNS*

*Northrop Services, Inc., and †U.S. Environmental Protection Agency, 200 S.W. 35th Street, Corvallis, Oregon 97333

A range of plant species, including crops, shrubs, herbs, and trees, was surveyed to determine the magnitude of isoprene emissions. In studies to determine if plants emitted isoprene, greenhouse-grown plants were encapsulated in impermeable plastic bags and kept in a growth chamber for 2 h at 30 C and a photosynthetic photon flux density of ca. 350 μE m^{-2} s^{-1}. To estimate emission rates, greenhouse-grown plants were conditioned in a growth chamber and transferred to a controlled-environment gas-exchange chamber. Gas samples from either the encapsulation bags or gas-exchange chamber were collected, concentrated cryogenically, and analyzed by gas-liquid chromatography. The occurrence of isoprene and monoterpenes was confirmed by combined gas chromatography–mass spectrometry. Of the 54 plant species tested, 37 emitted isoprene. Isoprene emission rates (28 C and 1,000 μE m^{-2} s^{-1}) for 16 species ranged from 0 to 38.5 μg carbon g^{-1} h^{-1}. Monoterpenes were detected from six species and emission rates ranged from 0.01 to 3.53 μg carbon g^{-1} h^{-1}. The encapsulation technique permitted rapid identification of species that emitted isoprene. The emission rate data confirmed the preliminary isoprene ranking and demonstrated the differences between monoterpene and isoprene emissions.

Introduction

Isoprene (2-methyl-1,3-butadiene) has been identified as a volatile emission product from several plant species (SANADZE 1961; RASMUSSEN 1970, 1972; TINGEY et al. 1979). The occurrence of isoprene has not been widely studied and has been reported primarily from dicotyledonous tree species (SANADZE 1961; RASMUSSEN 1970, 1972; ZIMMERMAN 1979). Most isoprene emission studies have used detached stems, leaves, twigs, or leaf disks in chambers with no air exchange (SANADZE and KURSANOV 1966; RASMUSSEN 1970; RASMUSSEN and JONES 1973). However, the lack of air exchange may result in an inaccurate estimation of emission rates (TINGEY and BURNS 1980) because temperatures (air and leaf) and humidity may exceed ambient levels and hydrocarbon gases accumulating within the chamber will decrease their diffusion gradients (TINGEY and BURNS 1980; STRAIN 1980). Also, the CO_2 concentration may be either depleted or elevated, thus influencing plant metabolism and stomatal aperture.

The objectives of this study were (1) to survey a wide range of plant species, including field crop, shrub, herb, and tree species, to determine their relative magnitude of isoprene emissions; and (2) to develop isoprene emission rate estimates for a range of species, using intact plants in a dynamic mass-balance gas-exchange chamber under conditions simulating the gaseous environment of plants in the field.

Manuscript received January 1982; revised manuscript received March 1982.

Material and methods

PLANT SELECTION AND CULTURE

Initially, 54 plant species representing a range of field crop, shrub, herb, and tree species were cultured from seed or stem cuttings in 15-cm pots in Pro Mix BX growth medium (Premier Brands, Inc., New Rochelle, N.Y.). The plants were greenhouse grown as described by TINGEY et al. (1979) and used when they reached 15–25 cm tall. The crop and herb species ranged from 16 to 30 days old, and the shrub and tree species from 3 to 24 mo old, respectively. All plants had both mature and young expanding leaves and appeared healthy. Following initial screening studies, selected species used to estimate emission rates under controlled conditions were conditioned in a controlled-environment chamber for a minimum of 4 wk at day/night temperatures of 29 ± 2/20 ± 2 C, with a 16-h photoperiod. Light was provided by both cool-white fluorescent (3,800 W) and incandescent (670 W) lamps yielding a photosynthetic photon flux density (PPFD) of 350 μE m^{-2} s^{-1}.

ISOPRENE SCREENING

A modified whole-plant encapsulation technique was used to identify species that emitted isoprene (RODECAP and TINGEY 1981). The soil and root mass was enclosed in a B620 Barrier Bag (Cryovac Division, W. R. Grace & Co., Cedar Rapids, Iowa) sealed at the stem; a separate bag was used to encapsulate the foliage. The encapsulated plants were kept for 2 h in a growth chamber at 30 C and a PPFD of ca. 350 μE m^{-2} s^{-1}. Preliminary isoprene emission readings were based on the total isoprene emissions per gram leaf dry weight for three replicates of each of the 54 selected plant species.

Emission rate determination

Emission rates were determined under controlled environment conditions with a dynamic mass-balance gas-exchange chamber (Tingey et al. 1979). The controlled-environment chamber contained the gas-exchange chamber, provided cooling, and housed a high-intensity-discharge sodium vapor lamp (Lucalox HPS, 1,000 W, General Electric Co., Cleveland, Ohio). Ambient air entering the gas-exchange chamber was purged of hydrocarbons, CO_2, and water vapor with an AADCO pure air generator (AADCO, Inc., Rockville, Md.). The CO_2 was returned to the airstream, as necessary, to maintain a concentration of 350 ± 20 μl liter^{-1} in the gas-exchange chamber.

During experimentation, the dew point of the air entering the gas-exchange chamber was constant at ca. −17 C; dew point of the air leaving the chamber varied between −9 and +32 C, depending on the particular plant species. The airflow rate into the chamber was measured at the chamber inlet port. Carbon dioxide, dew point, and hydrocarbons were measured at both the chamber inlet and outlet ports. Air temperature within the gas-exchange chamber was monitored with a shielded and aspirated thermocouple and leaf temperature with a thermocouple pressed against the abaxial surface. The PPFD at canopy height was measured with a LI-COR Model LI-190SR Quantum Sensor (Lambda Instruments Corp., Lincoln, Nebr.). Emission rates for selected plant species were estimated at a leaf temperature of 28 ± 1 C and a PPFD of 1,000 μE m^{-2} s^{-1}, using the gas-exchange chamber for 1–8 h. After each experiment, the leaves were removed to determine leaf area and dry weight.

The relationship between means and standard deviations for isoprene and monoterpene emissions indicated that they followed lognormal statistical distributions. Therefore, the data were transformed to their respective logarithms (Snedecor and Cochran 1968) and used as geometric means. Geometric means for 5–12 plants of each species were used to compute isoprene and monoterpene emission rates based on the theory of mass balance of gases, using gas flux rate equations (Tingey, Evans, and Gumpertz 1981).

Isoprene/monoterpene sampling and analysis

Duplicate 50-ml air samples were collected from either the encapsulation bags or the sample ports of the gas exchange chamber with gas-tight syringes (Precision Sampling Corp., Baton Rouge, La.). The samples were injected through a K_2CO_3 filter to remove water and were cryogenically concentrated (Tingey et al. 1979). Isoprene and monoterpenes were separated on a 3 m × 0.32 cm stainless steel column of Porasil E with 10% CS-10 (Alltech Associates, Deerfield, Ill.) as the stationary phase, utilizing a temperature program from 60 to 150 C with an increase of 24 C min^{-1}; the hydrocarbons were quantified with a flame-ionization detector with a minimum detectable limit of 5 pg carbon s^{-1}. The gas chromatograph detector was standardized daily by injecting three to six replicates of 2,2,4-trimethylpentane (4.3 ng) with a reproducibility of ±2%. A 99.9% pure isoprene standard and standards of each monoterpene were used to establish the isoprene and monoterpene retention times and profiles.

Identification of isoprene and monoterpenes emitted by selected plant species was made by a combination of gas-liquid chromatography and mass spectrometry (Tingey et al. 1979, 1980). Air samples from the gas-exchange chamber were collected, cryogenically concentrated, and chromatographed as described above. To confirm identification, isoprene and monoterpene mass spectra from the air samples were compared with spectra in the registry of mass spectral data (Stenhagen, Abrahamsson, and McLafferty 1974) and spectra from isoprene and monoterpene standards.

Results

Isoprene screening

Based on the screening tests, the species were divided into four groups—high, medium, low, and nondetectable—based on the relative isoprene emissions per gram dry weight of leaf tissue; actual ranges of emissions are listed in table 1. Of the 54 species tested, 37 emitted from 0.01 to 33 μg carbon g^{-1} isoprene, and the species were distributed throughout a diverse selection of plant species within the Pteridophyta, Coniferophyta, and the Monocotyledoneae and Dicotyledoneae of the Anthophyta. Measurable emissions occurred in at least one species in all but seven of the 21 families tested. The relative magnitude of isoprene emissions was diverse, both within and among families. Isoprene emissions within the Pinaceae ranged from essentially 0–30 μg carbon g^{-1} dry weight while emissions varied from a high of 34 μg carbon g^{-1} dry weight in the Salicaceae to less than 0.01 μg carbon g^{-1} dry weight in the Solanaceae (table 1). In addition, there was a large range of variation within species.

In general, the highest isoprene emissions were found among the tree and shrub species; low to nondetectable isoprene emissions were primarily found among the herbaceous or crop species. *Eschscholzia californica*, *Pueraria lobata*, and *Arachis glabrata* were the exceptions with medium to high isoprene emissions ranging from 1 to 20 μg carbon g^{-1} dry weight. However, seven shrub and tree species also had nondetectable isoprene emissions; these included three *Pinus* species, *P. monticola*, *P. elliottii*, and *P. contorta*, in addition to *Lithocarpus densiflora*, *Acer rubrum*, *Acer saccharum*, and *Ceanothus maritimus*.

TABLE 1

PLANT SPECIES RANKING BASED ON ISOPRENE SCREENING

Class and family	Isoprene emission ranking[a]			
	High	Medium	Low	Nondetectable
I. *Pteridophyta:*				
Cyatheaceae		*Dicksonia antarctica*		
Polypodiaceae		*Thelypertis decursive-pinnata*		
		Thelypteris dentata		
II. *Coniferophyta:*				
Pinaceae	*Picea engelmannii*	*Picea sitchensis*		*Pinus monticola*
				Pinus contorta
				Pinus elliottii
III. *Anthophyta:*				
Dicotyledoneae:				
Aceraceae				*Acer rubrum*
				Acer saccharum
Asclepiadaceae				*Asclepias speciosa*
Berberidaceae	*Berberis aquafolium*			
Betulaceae			*Betula papyrifera*	
			Betula lutea	
Chenopodiaceae				*Beta vulgaris*
Cruciferae				*Brassica oleracea*
Fagaceae		*Quercus borealis*		*Lithocarpus densiflora*
		Quercus virginiana		
Hamamelidaceae		*Liquidambar styraciflua*		
Labiatae				*Salvia mellifera*
Leguminosae		*Cystisus multiflorus*	*Phaseolus vulgaris*	*Vicia faba*
		Pueraria lobata	*Pisum sativum*	*Vicia pannonica*
		Robinia pseudoacacia	*Vigna unguiculata unguiculata*	
		Arachis glabrata	*Cercis canadenis*	
			Gleditsia triacanthos	
			Glycine max	
			Lathyrus latifolius	
			Lupinus albicanlis	
			Medicago sativa	
			Trifolium pratense	
			Lotus pedunculatus	
			Lotus corniculatus var. *arvensis*	
			Arachis hypogaea	
Malvalaceae				*Gossympium hirsutum*
Myrtaceae	*Eucalyptus globulus*			
Papaveraceae	*Eschscholzia californica*			
Platanaceae		*Platanus occidentalis*		
Rhamnaceae		*Rhamnus californica*		*Ceanothus maritimus*
Salicaceae	*Populus deltoides*	*Salix nigra*		
	Populus tremuloides			
Solanaceae				*Solanum tuberosum*
				Nicotiana tabacum
Monocotyledoneae:				
Gramineae			*Zea mays*	*Sorghum vulgare*
			Triticum aestivum	

[a] Ranking was based on the total isoprene emissions per gram leaf dry weight for three replicates of each plant species. The ranges were: high, 10–33 μg C g^{-1}; medium, 1–10 μg C g^{-1}; low, 0.01–1.1 μg C g^{-1}; and nondetectable isoprene emissions, <0.01 μg C g^{-1}.

The majority of the dicotyledonous tree species tested were consistently medium to high isoprene emitters. In contrast, the leguminous species tested, of which 80% were herbaceous, were primarily low isoprene emitters. Of the six highest ranked isoprene emitters, five were within the Dicotyledoneae. The three monocotyledonous species tested were low to nondetectable isoprene emitters. The three ferns tested, from two different families, were all classified as medium isoprene emitters.

Emission rate determination

Sixteen plant species, initially tested for their relative magnitude of isoprene emissions by the static-encapsulation technique, were studied under controlled conditions in the dynamic mass-balance gas-exchange chamber (table 2). *Eucalyptus globulus* had the highest isoprene emission rate, 38.5 μg carbon g^{-1} h^{-1}, and *Cercis canadensis* had the lowest, 0.013 μg carbon g^{-1} h^{-1}. Emission rates of two of the highest isoprene emitters, *Populus tremuloides* and *Populus deltoides*, differed by ca. 35% with low within-species variability (8%–9%), i.e., low standard geometric errors. However, in *Picea engelmannii* and *Picea sitchensis*, the isoprene emission rates differed by a factor of 4 and the variation of emission rates within a species was also larger (12%–28%) than within the *Populus* species.

Four species (table 2) emitted from three to five monoterpenes in addition to isoprene. However, isoprene was still the major volatile emission product for these species, equaling from 76%–85% of the total hydrocarbon emissions detected. Two species, *P. elliottii* and *A. saccharum*, emitted only monoterpenes. Of the species emitting monoterpenes, α-pinene was common to all and was emitted at the highest rate except for 1,8-cineole and sabinene from *E. globulus* and *A. saccharum*, respectively. Five of the monoterpene-emitting species also emitted β-pinene, but the remaining monoterpenes were common to only one or two species.

Discussion

The static encapsulation technique was useful in identifying the presence and relative magnitude of isoprene emissions from a wide range of species. The relative rankings of the high and low isoprene emitters were similar with both the static encapsulation and the gas-exchange chamber techniques. However, some of the species classified as medium isoprene emitters were found to be high emitters when studied in the gas-exchange chamber (table 2). The static encapsulation and similar enclosure techniques (Rasmussen 1972; Zimmerman 1979) may result in unreliable estimates of emissions because of modification of the environmental conditions near the plant, including changes in the CO_2 levels, increased humidity, and elevated temperatures due to inadequate airflow (Tingey and Burns 1980; Dimitriades 1981). In a field study comparing micrometeorological sampling and enclosure techniques, Quarles, Lamb, and Robinson (1980) found that the latter increasingly underestimated emission rates as the ambient temperature decreased. Thus, enclosure techniques appear to have drawbacks but, when used conservatively, may be useful for indicating the presence and relative magnitude of hydrocarbon emissions.

The flux of a gas between a plant and the environment is proportional to the chemical potential gradient for the gas and the permeability of the diffusive pathway. The chemical potential gradient that drives isoprene and monoterpene emissions from leaves into the atmosphere is the vapor pressure of the individual gases. The vapor pressures of the individual gases are proportional to their respective concentrations and leaf temperature. Jones and Rasmussen (1975) and Tingey et al. (1981) indicated that stomatal conductance was not as important as the isoprene biosynthetic rate in controlling emissions. In our study, leaf temperatures were held constant and would not affect emission rates; therefore, only the isoprene pool size would influence the chemical potential gradient driving emissions. If the pool sizes were constant, isoprene emissions should have been constant among species; however, wide ranges in emission rates were observed from a variety of plant species, supporting the role of biosynthesis or pool size in controlling isoprene emissions.

The nine monoterpenes (table 2) detected in this study occur within six closely related biogenetic/structural types of monoterpenes (Devon and Scott 1972) which vary structurally by as little as the conversion or placement of a double bond. These six categories form the central portion of 15 well-defined biogenetic/structural categories which, with 15 less common skeletons, are used to index ca. 400 different monoterpenes (Devon and Scott 1972).

The monoterpenes detected in the foliar emissions appear to be limited by factors controlling the vapor phase concentrations within the leaves, including liquid phase concentration and vapor pressure. Monoterpenes with appreciable vapor pressures at ambient temperatures are likely to be emitted at significant rates (Tingey and Burns 1980). A specific example of how these factors influence foliar emissions occurred in *Eucalyptus globulus*, where linalool and terpineol were detected in leaf extracts (Masada 1976) but were not detected in the foliar emissions in this study. At 28 C, the vapor pressures of linalool and terpineol are 0.59 and 0.46 mm Hg (Jordan 1954), respectively, and the lowest vapor pressure of monoterpenes detected in this study was 1.80 mm Hg at 28 C (β-Phellandrene), approximately three and a half times higher than the vapor pressures of linalool and terpineol.

The qualitative relationships among the mono-

TABLE 2

COMPARISON OF EMISSION RATE ESTIMATES FOR SELECTED PLANT SPECIES AT A LEAF TEMPERATURE OF 28 C AND LIGHT INTENSITY OF 1,000 μE m^{-2} s^{-1}

Plant species	No.	Isoprene (μg C/g h)	Monoterpenes (μg C/g h)									Total emission rates detected (μg C/g h)	Percent isoprene of total hydrocarbon detected	Isoprene emission rate ranking
			α-Pinene	*Camphene*	*β-Pinene*	*Myrcene*	*Ocimene*	*β-Phellandrene*	*1,8 Cineole*	*Limonene*	*Sabinene*			
Eucalyptus globulus	8	38.50 (1.10)	1.14 (1.11)	...	.58 (1.25)	...	.84 (1.24)	...	3.53 (1.24)	.69 (1.34)	...	45.28	85%	High
Populus tremuloides	8	33.89 (1.08)	...	...	...	...	...	...	...	...	...	33.89	100%	High
Populus deltoides	8	24.95 (1.09)	...	...	...	...	...	...	...	...	...	24.95	100%	High
Rhamnus californica	5	19.80 (1.07)	...	...	...	...	...	...	...	...	...	19.80	100%	(Medium)[a]
Platanus occidentalis	7	18.55 (1.29)	...	...	...	...	...	...	...	...	...	18.55	100%	(Medium)
Salix nigra	12	17.00 (1.11)	...	...	...	...	...	...	...	...	...	17.00	100%	(Medium)
Thelypteris decursive-pinnata	8	16.50 (1.05)	...	...	...	...	...	...	...	...	...	16.50	100%	(Medium)
Quercus borealis	7	13.33 (1.16)	...	...	...	...	...	...	...	...	...	13.33	100%	(Medium)
Liquidambar styraciflua	12	12.00 (1.10)	1.20 (1.17)	...	.35 (2.33)	...	...	...	...	.57 (1.98)	...	14.12	85%	(Medium)
Picea engelmannii	12	11.00 (1.12)	1.40 (1.26)	.17 (2.14)	.65 (1.32)	.10 (1.97)	...	.19 (2.14)	...	...	...	13.51	81%	High
Pueraria lobata	8	6.45 (1.36)	...	...	...	...	...	...	...	...	...	6.45	100%	Medium
Picea sitchensis	12	2.70 (1.28)	.21 (1.31)	.13 (1.14)	.18 (1.31)	.32 (1.13)	...	.00[b] (2.44)	...	...	...	3.54	76%	Medium
Glycine max	9	.018 (1.14)	...	...	...	...	...	...	...	...	...	.018	100%	Low
Cercis canadensis	4	.013 (1.19)	...	...	...	...	...	...	...	...	...	.013	100%	Low
Pinus elliottii	5	...	2.79 (1.19)	...	2.00 (1.17)	.19 (1.19)	...	.14 (1.21)	...	.01 (1.15)	...	5.13	0%	Nondetectable
Acer saccharum	8	...	.45 (1.31)	.21 (1.14)	...	.38 (1.16)	...	...	...	...	.58 (1.44)	1.62	0%	Nondetectable

NOTE.—Three dots indicates that these compounds were not detected in the emission profiles by the methods used in this study. The values in parentheses are the standard geometric errors ($\exp[\sqrt{MSE}/\sqrt{n}]$).

[a] Preliminary ranking resulting from screening encapsulation when different from final ranking.

[b] This compound was detected in the foliar emissions of only one of the 12 plants tested.

terpene emissions for each plant species in this study agreed with the findings of others who used oleoresin or steam distillation extracts of the needles or leaves of the same species (VON RUDLOFF 1964; MASADA 1976; EKUNDAYO 1978). RASMUSSEN (1972) noted the dominance of five to six monoterpene types in both the foliar emissions and extracted oils of a variety of species. VON RUDLOFF (1964), MASADA (1976), and EKUNDAYO (1978) observed a variety of monoterpenes, including oxygenated compounds in leaf oil extracts, from *Picea*, *Pinus elliottii*, and *Eucalyptus globulus* as well as from other species, which we did not detect in the foliar emissions from these same species in the present study.

HANOVER (1972) showed a general correspondence between the volatiles present in the oleoresin extracts and those in the gas phase surrounding the foliage of *Pinus monticola*, although he observed that there were quantitative differences, that α-pinene and camphene were usually higher in the vapor than in the oleoresin while Δ^3-carene was usually higher in the oleoresin. These differences appear to be related to the vapor pressure of the monoterpenes, since those monoterpenes with higher vapor pressures at ambient temperatures would be volatilized at faster rates than those with lower vapor pressures even though both were present in equal tissue concentrations.

RASMUSSEN (1970) suggested that foliar disturbance by handling or wind was an additional factor increasing monoterpene emissions because he was unable to detect monoterpenes from undisturbed foliage of *Liquidambar styraciflua* and *Eucalyptus* sp. In our study, isoprene and monoterpenes were detected from both of these species during the entire study. The plants were undisturbed since they were placed in the chamber 16 h in advance of initial emission measurements; emission rates were measured over 1–8 h and there was no recent handling of the plants. In addition, the air-circulating fan was adjusted so that no leaf flutter occurred, and the plants were small enough to ensure that there was no foliar contact with the walls of the gas-exchange chamber. Since the monoterpene emissions are much lower than the isoprene emissions in both of these species, it is possible that the monoterpene emissions were below the detection limits in RASMUSSEN's (1970) study or the effects of movement persist for a long period.

The vapor pressures of monoterpenes detected in the gas phase in our study ranged from 1.80–6.30 mm Hg at 28 C, compared with 640.12 mm Hg at 28 C for isoprene (JORDAN 1954), which could be an important factor explaining the slower emission rates of monoterpenes than of isoprene. Isoprene emission rates varied widely both among isoprene-emitting species and species that emitted isoprene and monoterpenes. Overall, the isoprene emission rates averaged approximately four times the monoterpene emission rates. The monoterpene emission rates were similar among species that emitted only monoterpenes and those species that emitted both monoterpenes and isoprene. This implies that monoterpene emissions are not influenced by isoprene biosynthesis. Although isoprene biosynthesis and/or pool size are the primary factors controlling isoprene emission, the vapor pressure of isoprene clearly influences the isoprene emission rate when compared with the monoterpene emission rates. With a vapor pressure 100 times larger than the monoterpenes, it would only require a very small pool of isoprene before the isoprene emission rates would be significant. In contrast, the monoterpenes have such low vapor pressures that a significant pool would be required before it would be possible to detect their emission.

Acknowledgment

This research was supported by contract 68-03-2650 with the Environmental Protection Agency.

LITERATURE CITED

DEVON, T. K., and A. I. SCOTT. 1972. Handbook of naturally occurring compounds. Vol. 2. Terpenes. Academic Press, New York and London.

DIMITRIADES, B. 1981. The role of natural organics in photochemical air pollution: issues and research needs. J. Air Pollution Control Assoc. **31**:229–235.

EKUNDAYO, O. 1978. Monoterpene composition of the needle oils of *Pinus* species. J. Chromatography Sci. **16**:294–295.

HANOVER, J. S. 1972. Factors affecting the release of volatile chemicals by forest trees. Mitteilungen Forstlichen Bundes-Versuchanst Wien **97**:625–644.

JONES, C. A., and R. A. RASMUSSEN. 1975. Production of isoprene by leaf tissue. Plant Physiol. **55**:982–987.

JORDAN, T. E. 1954. Vapor pressures of organic compounds. Interscience, New York.

MASADA, Y. 1976. The analysis of essential oils by gas chromatography and mass spectrometry. Wiley, New York.

QUARLES, T., B. LAMB, and E. ROBINSON. 1980. Measurements of isoprene fluxes from a northeastern deciduous forest. Reprint 80-69.3. Annu. Meeting Air Pollution Control Assoc., June 22–27, 1980, Montreal.

RASMUSSEN, R. A. 1970. Isoprene: identified as a forest-type emission to the atmosphere. Environmental Sci. Technol. **4**:667–671.

———. 1972. What do hydrocarbons from trees contribute to air pollution? J. Air Pollution Control Assoc. **22**:537–543.

RASMUSSEN, R. A., and C. A. JONES. 1973. Emission isoprene from leaf discs of *Hamamelis*. Phytochemistry **12**:15–19.

RODECAP, K. D., and D. T. TINGEY. 1981. Stress ethylene: a bioassay for rhizosphere-applied phytotoxicants. Environmental Monitoring and Assessment **1**:119–122.

SANADZE, G. A. 1961. Absorption of molecular hydrogen by illuminated leaves. Soviet J. Plant Physiol. **8**:443–446.

SANADZE, G. A., and A. L. KURSANOV. 1966. On certain conditions of evolution of the diene C_5H_8 from popular leaves. Soviet J. Plant Physiol. **13**:184–189.

SNEDECOR, G. W., and W. G. COCHRAN. 1968. Statistical methods. 6th ed. Iowa State University Press, Ames.

STENHAGEN, E., S. ABRAHAMSSON, and F. N. MCLAFFERTY. 1974. Registry of mass spectral data. Wiley, New York.

STRAIN, B. 1980. Physiological effects of simulated environments on green plants. Pages 53–72 *in* J. J. BUFALINI and R. R. ARNTS, eds. Atmospheric biogenic hydrocarbons: emission rates, concentrations and fate. Vol. 1. Ann Arbor Science, Ann Arbor, Michigan.

TINGEY, D. T., and W. F. BURNS. 1980. Hydrocarbon emissions from vegetation. Pages 24–30 *in* Effects of air pollutants on mediterranean and temperate forest ecosystems. USDA, Forest Service General Tech. Rep. PSW-43. 256 pp.

TINGEY, D. T., R. EVANS, and M. GUMPERTZ. 1981. Effects of environmental conditions on isoprene emission from live oak. Planta **152**:565–570.

TINGEY, D. T., M. MANNING, L. C. GROTHAUS, and W. F. BURNS. 1979. The influence of light and temperature on isoprene emission rates from live oak. Physiol. Plantarum **47**:112–118.

———. 1980. Influence of light and temperature on monoterpene emission rates from slash pine. Plant Physiol. **65**: 797–801.

VON RUDLOFF, E. 1964. Gas-liquid chromatography of terpenes. X. The volatile oils of the leaves of Sitka and Englemann spruce. Can. J. Chem. **42**:1057–1062.

ZIMMERMAN, P. R. 1979. Determination of emission rates of hydrocarbons from indigenous vegetation in the Tampa/St. Petersburg, Florida area. *In* Tampa Bay area photochemical oxidant study, Appendix C. EPA-904/9-77-028. U.S. Environmental Protection Agency, Region IV, Atlanta, Ga. 91 pp.